SPECTROSCOPIC INVESTIGATION OF INTENSE PULSED DISCHARGES IN HYDROGEN. II

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The spectral properties of the radiation from the hydrogen plasma in a low-pressure gas discharge at currents up to 500 kiloamperes have been studied by means of a mirror-sweep method. Using this method it is possible to study the behavior of the gas discharge in the visible region as a function of time. During contraction of the plasma pinch a continuous-spectrum "flash" is observed. Results obtained in experiments in which nitrogen and helium were added indicate a high electron temperature in the plasma when contraction takes place. An estimate of the charged particle concentration is made on the basis of the broadening of the H_α line.

1. INTRODUCTION

THE presently available spectroscopic data for pulsed, low-pressure, high-current discharges (approximately 10^5 amperes[1]) yield comparatively scanty information on the development of the discharge. These data are relatively incomplete because they are obtained over the entire duration of the discharge, thereby yielding the "integrated" characteristics of the process. Valuable additional information can be obtained from a knowledge of the intensity of the spectral lines as a function of time; the appropriate measurements can be easily carried out using a photoelectric cell in conjunction with a monochromator. However, this method is inconvenient because of the impossibility of simultaneous photometric measurements of all the spectral lines. Moreover, in experiments of this kind, it is difficult to study another important parameter — the width of the spectral line. Among other things, a knowledge of the half width of the spectral line is extremely important for establishing the time variation of the density of charged particles in the plasma. It should also be kept in mind that without some sort of time-sweeping arrangement it is difficult to observe the extremely short-lived lines due to multiply charged ions which are produced in the discharge when atoms of other materials are introduced artificially.

The identification and time variation of the intensity of these lines can be extremely important in estimating the electron temperature in the plasma at various instants of time.

These considerations were the motivation for carrying out an investigation of the time variation of spectra of pulsed discharges. Time sweep was obtained by use of the rotating-mirror method.[2] A Kerr cell would be less effective because the emission from the discharge at times long after the initiation of the discharge is tens and even hundreds of times greater than that which obtains when the discharge is initiated; the latter is of greatest interest in studying the development of the discharge.

Since the transmission of a Kerr cell cannot be reduced to zero even when it is "closed", the intense and long-lived emission characteristic of the later stages of the discharge would tend to mask the weak spectrum characteristic of the initial stages.

2. APPARATUS AND METHOD OF MEASUREMENT

The experimental conditions were essentially the same as those described earlier in Ref. 1. The pulsed system consisted of a condenser bank with a capacity of 86 μfd and a discharge chamber made from a porcelain tube with inner diameter of 400 mm. The distance between the copper electrodes of the discharge chamber was 900 mm. The discharge chamber was furnished with a side port covered with a quartz plate. The central region of the discharge could be ovserved through the window in the port (see Fig. 1).

The discharge chamber was filled from a measured volume; the hydrogen was first passed through a palladium filter. In the experiments in which gaseous mixtures of hydrogen and helium were used the helium was spectrally pure.

A Rogovskii loop was used to measure the current; with an initial voltage of 40 kv across the condenser bank the maximum current strength was 460

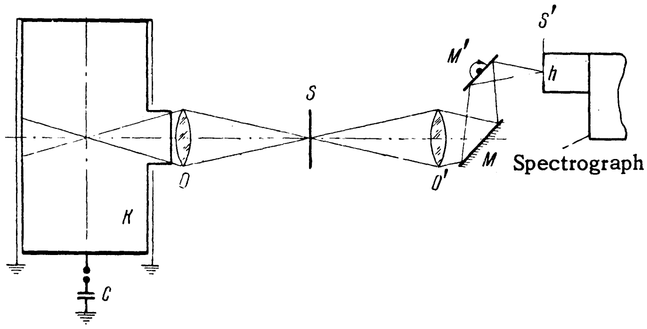

FIG. 1. Optical diagram for the spectral sweep system. D) discharge chamber; O and O′) objectives; S) intermediate slit, the image of which is obtained as a band in the plane S′; M and M′) fixed mirror and rotating mirror respectively; h) height of the slit of the spectrograph.

kiloamperes. The stray inductance in the discharge circuit was small and under the conditions indicated the initial rate-of-rise of the current was 1.5×10^{11} amps/sec. The first contraction started 3 — 4 microseconds after the discharge was initiated.

The method of obtaining the time sweep for the spectrum is as follows. The optical system forms a light beam from the visible radiation emitted from a definite section of the luminous volume of the discharge chamber; in the plane of the entrance slit of the spectrograph, this beam forms an image of the intermediate slit in the form of a narrow band. If this band is perpendicular to the entrance slit of the spectrograph, its width determines the wavelength of the spectral lines which are observed in the focal plane of the camera of the spectrograph. By using a rotating mirror it is possible to displace the luminous band along the entrance slit of the spectrograph. Thus the entire spectrum is swept in wavelength as a function of time. A schematic diagram of the optical system is shown in Fig. 1. The optical system is designed so that there are no limiting apertures for the light beam as the luminous band is displaced along the input slit.

The sweep speed is determined by the distance from the rotating mirror to the plane of the input slit and by the rotational velocity of the mirror. In the present scheme, with $n = 15{,}000$ rpm and $h = 12$ mm, the total sweep time was 20 microseconds. The time required for the luminous band to be displaced by a natural line width (the resolving time) was approximately 0.7 microsecond in the experiments described here. The rotational velocity of the mirror was controlled to within 0.1 per cent by means of a special electron-beam tachometer unit.

The spectral time-variation pattern can be synchronized with the discharge current. For this purpose a cross hair is placed across the input slit of the spectrograph; this cross hair produces a fiduciary mark on all the spectral lines. A small mirror is placed at the level of the cross hair; when the luminous band passes through the cross hair light is reflected on to the cathode of a photomultiplier. Thus, one beam of the oscilloscope is used to display the discharge current curve while the signal obtained from the photomultiplier is applied to the other beam and serves as an indication of the point in the discharge which corresponds to the fiduciary mark on the spectral sweep.

3. RESULTS OF THE MEASUREMENTS

In Fig. 2 are shown time-swept discharge spectra for several typical cases; these spectra were obtained with a condenser-bank voltage of 35 kv. The first two spectra (2a and 2b) were obtained using a discharge in pure hydrogen at initial pressures $p_0 = 0.05$ mm Hg and 0.1 mm Hg. In the spectrum marked 2c are shown data obtained by photographing the spectrum of a discharge in a mixture of hydrogen and nitrogen (95 per cent H_2 + 5 per cent N_2), 2d was obtained with a mixture of hydrogen and helium (70 per cent H_2 + 30 per cent He). For convenience, the current oscillogram corresponding to each spectrogram is also shown. The sweep speeds are the same for the spectra and oscillograms.

Under the conditions being considered here the intensity of the H_α line is 15 — 20 times greater than the intensity of the H_β line and greater still than the H_γ line (cf. for example, Fig. 4 of Ref. 1).

The spectra were photographed with panchromatic aerial plates with a sensitivity of 1,000 GOST units, having maximum sensitivity in the red portion of the spectrum; hence of all the lines of the Balmer series only the H_γ line was recorded.

An interesting characteristic of several of the spectrograms is the coninuum flash which occurs at maximum contraction of the plasma pinch (first break in the current oscillogram). The continuous background is small for the hydrogen discharge (with $p_0 = 0.05$ mm Hg it is generally not noticeable) and fairly small when helium is added; however, when even small amounts of nitrogen are added the background becomes very pronounced (cf. Spectrogram 2c). In addition to the continuum, on Spectrograms 2c and 2d there are observed lines, which as a rule, fade out in later stages of the discharge. The origin of these lines is considered below.

In the red region of the spectrum, the spectrograph dispersion is small so that a reliable analysis of the line shape can be made only for well separated lines. In Fig. 3 is shown the time be-

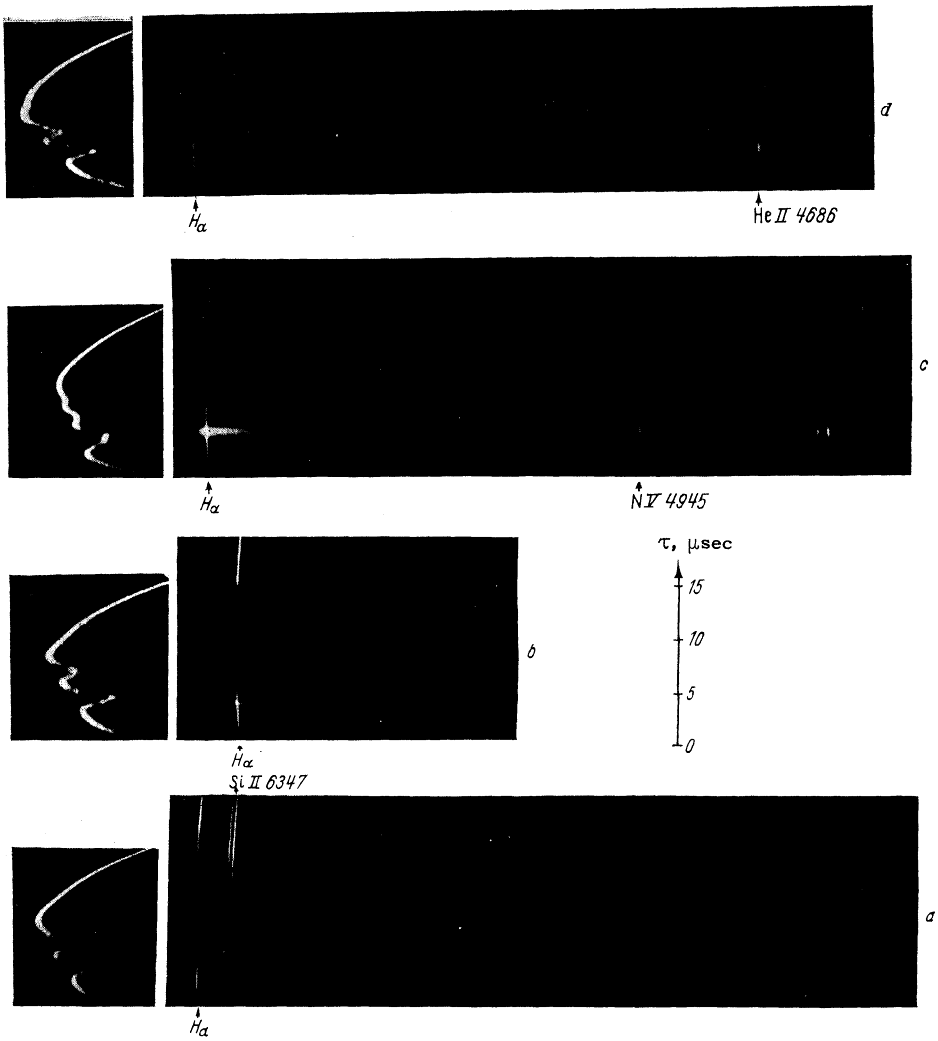

FIG. 2. Spectrogram of the pulsed discharge under various conditions. a) pure hydrogen, $p_0 = 0.05$ mm Hg; b) pure hydrogen, $p_0 = 0.1$ mm Hg; c) 95 per cent H_2 plus 5 per cent N_2, $p_0 = 0.05$ mm Hg; d) 70 per cent H_2 plus 30 per cent He, $p_0 = 0.05$ mm Hg.

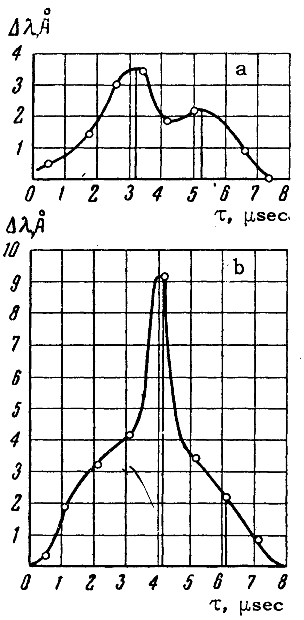

FIG. 3. Time variation of the half-width of the H_α line: a) $p_0 = 0.05$ mm Hg. b) $p_0 = 0.1$ mm Hg. The vertical lines denote the first and second contractions of the pinch.

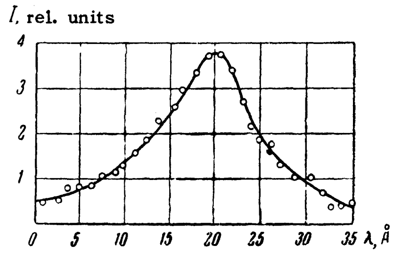

FIG. 4. Shape of the H_α line at maximum contraction, $p_0 = 0.1$ mm Hg, $\tau = 4.2$ microseconds.

havior of the half width of the H_α line for two values of the pressure. In view of what has been indicated the data for $p_0 = 0.1$ mm Hg are much more reliable. As an illustration, in Fig. 4 is shown the line shape for the H_α line at the instant of time corresponding to contraction of the plasma pinch ($p_0 = 0.1$ mm Hg).

4. DISCUSSION OF THE RESULTS

We first consider the spectrograms shown in Fig. 2. On all spectrograms, up to the instant at which contraction of the pinch takes place, only the H_α line of atomic hydrogen is observed. The absence of other lines in the Balmer series has already been explained. However, it is natural to wonder why the spectrograms do not exhibit nitrogen lines or helium lines in the cases in which the discharge tube is filled with a mixture of hydrogen and these gases. In the nitrogen case the absence of a nitrogen line is explained by the small percentage content of this gas; the fact that the nitrogen content was small was verified in control experiments. In the helium case the absence of He I lines is probably due to the rather high excitation energy (for example, 23 ev for the He I line at 5876 A but 12 ev for the H_α line at 6563 A).

If the discharge takes place in pure hydrogen, lines due to impurity atoms, which enter from the walls of the discharge chamber, are produced after the second contraction (for example, the Si II line at 6347 A in Fig. 2a). This result is in agreement with the data of photoelectric measurements.[1]

If the discharge takes place in a mixture of hydrogen and nitrogen or helium, as has already been noted, at maximum contraction of the pinch there appear short-lived spectral lines which are not observed in the subsequent stages of the discharge. These lines, which can be distinguished from the continuum background, should be assigned to nitrogen or helium (the emission of impurity atoms from the walls of the discharge chamber takes place later). However, these lines do not correspond to lines for neutral nitrogen or helium. Hence the observed lines were assigned to highly excited ionized helium and nitrogen. If the assignment of the N II, He II and N V 4619 lines is granted, the N V 4945 line is open to doubt since the wave length given in the Moore tables[3] is a calculated value which has not been verified experimentally before. The following experiment serves to corroborate this finding: the intensity of the broadened N V 4595 line increases continuously as nitrogen added is increased. Aside from the N V 4945 line the N V 4943 line is also observed in the corresponding part of the spectrum. A microphotogram of this region of the spectrum is

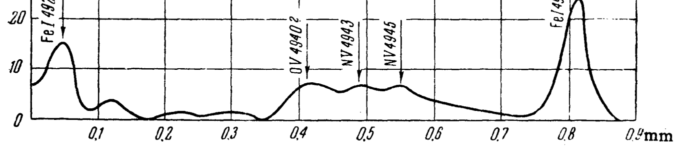

FIG. 5. Microphotogram of the spectrum in the neighborhood of 4950 A. The iron lines Fe I at 4957. 7A and at 4924.78 A are used as references.

TABLE I

Wave length A	Element	Excitation energy,* ev
4945	N V	90
4686	He II	51
4621	N II	21
4619	N V	59
4607	N II	21

*The excitation energy is computed from the ground state of the corresponding ion.

given in Fig. 5. In Table I are shown wave length values for some of the observed lines.

The unexpected appearance of these lines may be taken as an indication of a sudden increase in electron temperature at maximum contraction of the plasma pinch and as an indication of the conversion of the energy associated with the directed motion of the ions into heat. The temperature falls off in the subsequent expansion of the plasma and the lines corresponding to this high excitation vanish. It is interesting to note that in the second contraction these lines are again observed, although their intensities are much weaker.

One further circumstance must be explained in connection with the foregoing. In the initial stages of the discharge there are no nitrogen lines corresponding to small excitation energies; at maximum contraction, however, lines characterized by high excitation energies are observed. The probable cause for this effect is purely geometrical: the conditions for observing emission originating from the center of the discharge chamber are more favorable than those for observing emission distributed uniformly over the volume of the discharge chamber.

Since the electron temperature at the first contraction is sufficient for exciting lines of quadruply ionized nitrogen and lines of neutral helium and nitrogen are not observed, there is little doubt that the hydrogen is completely ionized (at least in certain sections of the inner zones of the discharge). It is clear that the emission of the H_α line observed at this instant is due to those sections of the plasma pitch in which the ionization is less than 100 per cent complete.

If the electron temperature at the first contraction reaches several thousands of electron volts*

*We may recall that the kinetic temperature of the ions, as estimated from the velocity of propogation of the contracting light fronts or magnetic field fronts, reaches 100 – 200 ev at the end of contraction.[1] An estimate of the temperature, obtained from the Doppler broadening of the nitrogen lines during contraction, yields the value $T_i \approx 300$ ev. The authors intend to return to this question.

an important role in the continuum spectrum being considered should be played by the "free-free" transitions, i.e., bremsstrahlung. The bremsstrahlung intensity and recombination radiation can be estimated from the following formulas[4]

$$I_1(\nu, T_e) = A_1 n_i n_e Z_{\text{eff}}^2 T_e^{-1/2} \exp\{-h\nu / kT_e\};$$
$$I_2(\nu, T_e) = A_2 n_i n_e Z_{\text{eff}}^4 T_e^{-3/2} \exp\{-h(\nu - \nu_n) / kT_e\} / n^3.$$

Here n_e and n_i are the electron density and ion density respectively, T_e is the electron temperature, Z_{eff} is the effective charge of the gas ions, n is the principal quantum number of the level from which recombination occurs, $h\nu_n$ is the energy of this level and A_1 and A_2 are universal constants. Applying these to hydrogen for radiation which occurs in the visible region of the spectrum (recombination to the n = 3 level) the values shown in Table II are obtained.

TABLE II

T_e, eV		1	3	10	30	100
$1/n_i n_e \int_{\nu_1}^{\nu_2} I_1 d\nu$	Relative units	23.4	60.0	58.7	41.0	25.6
$1/n_i n_e \int_{\nu_1}^{\nu_2} I_2 d\nu$	Relative units	107	34	6.85	1.41	0.23

As is apparent from the Table, even at an electron temperature of 30 ev, the bremsstrahlung predominates; there is relatively little change in the intensity of this radiation with further increase in temperature. Thus, even if the electron temperature is known with poor accuracy, if it is greater than 20 — 30 ev, the measurement of the intensity of the continuum gives an independent absolute method of determining the density of charged particles in the plasma.

The fact that the bremsstrahlung is proportional to Z_{eff}^2 and, the square of the density of charged particles is probably the explanation for the experimentally observed increase in the intensity of the continuum when helium and nitrogen are introduced and when the initial hydrogen pressure is increased.

As is apparent from Fig. 3, the H_α line is broadened rapidly as the plasma contracts.* The maximum broadening of the line is observed at the first contraction; in the second contraction, the broadening occurs at lower pressures and is scarcely noticeable at all at $p_0 = 0.1$ mm Hg. The line at maximum contraction (cf. Fig. 4) exhibits extended wings; these indicate that the Stark effect is responsible for broadening of the line. If we use the Holtzmark formula[6] to convert from the measured half-widths to ion densities, at the first contraction we obtain values which lie within the limits $0.3 \times 10^{17}\,\text{cm}^{-3}$ to $0.7 \times 10^{17}\,\text{cm}^{-3}$ in the various experiments. In the case being considered ($p_0 = 0.1$ mm Hg), the initial density of neutral atoms is $0.7 \times 10^{16}\,\text{cm}^{-3}$. Thus, there is a five- or ten-fold contraction. Actually, the contraction is greater than this since the ionization is less than 100 per cent complete in the region of the discharge in which the radiating hydrogen atoms are located.

*A similar result has been obtained recently in Ref. 5.

It is obvious that these estimates of ion density cannot be taken too seriously since they were obtained from an application of the Holtzmark formula in a high-temperature plasma. Actually, under these conditions, the theory should not apply. However, as has been shown by Kogan,[7] the relationship between the effective line width and density of charged particles still applies (with certain corrections in the numerical factors).

On the whole the optical data considered give an internally consistent picture of the phenomena which occur in a high-power pulsed discharge.

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Translated by H. Lashinsky
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